

# Heating of X-Ray Hot Gas in Groups by Blast Waves

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## ABSTRACT

In order to find the conditions which determine whether X-Ray hot gas in galaxy groups (intragroup gas; IGG) is heated externally or internally, we investigate the evolution of blast waves in galaxy groups growing on a hierarchical clustering scenario. We find that the blast waves driven by quasars are confined in groups and heat the IGG internally at  $z \lesssim 1$ . However, at  $z \gtrsim 1$ , they expel the IGG from groups; the expelled gas may fall back into the groups later as externally heated gas. Moreover, this may explain the observed low metal abundance of IGG. For blast waves driven by strong starbursts, the shift of the fate of blast waves occurs at  $z \sim 3$ . On the other hand, although blast waves driven by weak starbursts do not expel IGG from groups, the heating efficiency decreases at  $z \gtrsim 3$  because of radiative cooling. It will be useful to compare these results with XMM-Newton observations.

*Subject headings:* galaxies: clusters: general—intergalactic medium—quasars: general—galaxies: active—X-rays: galaxies: clusters

## 1. Introduction

X-ray properties of clusters and groups of galaxies show the thermal history of the X-ray gas (Kaiser 1991; Evrad and Henry 1991; Fujita and Takahara 2000). Simple theoretical models predict that the relation between X-ray luminosity and temperature should be  $L_X \propto T_X^2$ , if the thermal properties of X-ray gas have been determined only by the gravitational energy released at the time of the collapse. However, X-ray observations show that this is not true; from a rich cluster scale to a group scale, the exponent increases from  $L_X \propto T_X^{2-3}$  (e.g. David et al. 1993; Xue & Wu 2000) to  $L_X \propto T_X^5$  (Ponman et al. 1996; Xue & Wu 2000). Moreover, the discovery of the entropy excess in groups (‘entropy-floor’) by Ponman, Cannon and Navarro (1999) suggests that non-gravitational heating has especially affected the thermal properties of X-ray gas in groups (intragroup medium; IGG).

However, the heating sources have not been identified; they may be quasars or starburst galaxies (e.g. Valageas and Silk 1999). In order to know what are the dominant sources, it may be useful to investigate whether the entropy excess is the residual of the entropy originally present in the protocollapse medium or intergalactic medium (IGM) or whether it is generated within halos after collapse. Tozzi et al. (2000) showed that using XMM-Newton it would be possible to find whether IGG is *externally* or *internally* heated by observing entropy profiles at large radii in X-ray halos. If IGG is externally heated, we will detect the isentropic, low surface brightness emissions extending to radii larger than the virial ones in groups. However, even if we detect them, we need theoretical models to be compared. That is, we need the models describing what kind of heating source heats IGG externally.

Moreover, the epoch when the energy is released into IGG is still open to question. Yamada and Fujita (2000) consider the heating by AGN jets. Using a simple theoretical model, they estimated the Sunyaev-Zeldovich effect by the heated gas and compared it with the observations of the Cosmic Microwave Background. They concluded that the IGG is heated at  $z \lesssim 3$ . This suggests that the heating of IGG occurred after or simultaneously with the collapse of groups. However, they did not consider the heating by starburst galaxies. Moreover, they assumed that the energy is ejected into IGM with the density near to the average in the universe. In the actual universe, it is likely that AGNs reside in the region with IGM density higher than the average in the universe.

In this paper, for various heating sources we investigate when the sources heat IGG externally or internally. For that purpose, we consider the evolution of blast waves with different energies, because it is expected that heating sources (quasars or starburst galaxies) drive blast waves similar to supernova remnants (Voit 1996; Yamada et al. 1999). We assume that the heating sources responsible for the excess entropy in groups have resided in the groups or in the group progenitors; this assumption is valid unless each source can heat an extremely wide region of the universe. We explore whether the blast waves are confined in the groups (or in their progenitors) or whether they escape from the groups (or from their progenitors) and expel the IGG. In the former case, they serve as internal heating sources; since the hot gas region inside the wave is buoyant, it later mixes with the ambient gas through Rayleigh-Taylor instability. Moreover, subsequent mergers between groups may also make their IGG uniform. Thus, in that case we expect that the energy released by heating sources is effectively transferred into IGG. On the other hand, in the latter case, the expelled gas may fall back into the groups later as externally heated gas as the groups gather the ambient medium. We also investigate the radiative cooling of the blast waves. If it is effective, most of the energy ejected by heating sources is radiated before transferred into IGG.

## 2. Models

### 2.1. The Growth of Galaxy Groups

The conditional probability that a particle which resides in a object (‘halo’) of mass  $M_2$  at time  $t_2$  is contained in a smaller halo of mass  $M_1 \sim M_1 + dM_1$  at time  $t_1$  ( $t_1 < t_2$ ) is

$$P_1(M_1, t_1 | M_2, t_2) dM_1 = \frac{1}{\sqrt{2\pi}} \frac{\delta_{c1} - \delta_{c2}}{(\sigma_1^2 - \sigma_2^2)^{3/2}} \left| \frac{d\sigma_1^2}{dM_1} \right| \exp \left[ \frac{(\delta_{c1} - \delta_{c2})^2}{2(\sigma_1^2 - \sigma_2^2)} \right] dM_1, \quad (1)$$

where  $\delta_{ci}$  is the critical density threshold for a spherical perturbation to collapse by the time  $t_i$ , and  $\sigma_i [\equiv \sigma(M_i)]$  is the rms density fluctuation smoothed over a region of mass  $M_i$  for  $i = 1$  and 2 (Bond et al. 1991; Bower 1991; Lacey and Cole 1993).

We define the typical mass of halos at  $t$  that become part of a larger halo of mass  $M_0$  at later time  $t_0 (> t)$  as

$$\bar{M}(t | M_0, t_0) = \frac{\int_{M_{\min}}^{M_0} M P_1(M, t | M_0, t_0) dM}{\int_{M_{\min}}^{M_0} P_1(M, t | M_0, t_0) dM}, \quad (2)$$

where  $M_{\min}$  is the lower cutoff mass. We choose  $M_{\min} = 10^8 M_\odot$ , which corresponds to the mass of dwarf galaxies. In the following sections, we investigate the group whose virial mass is given by

$$M_{\text{vir}}(t | M_0, t_0) = \bar{M}(t | M_0, t_0). \quad (3)$$

From now on, we will represent  $M_{\text{vir}}(t | M_0, t_0)$  with  $M_{\text{vir}}$  unless it is misunderstood.

We assume that groups are spherically symmetric. The virial radius of a group with virial mass  $M_{\text{vir}}$  is defined as

$$r_{\text{vir}} = \left( \frac{3 M_{\text{vir}}}{4\pi \Delta_c(z) \rho_{\text{crit}}(z)} \right)^{1/3}, \quad (4)$$

where  $\rho_{\text{crit}}(z)$  is the critical density of the universe and  $\Delta_c(z)$  is the ratio of the average density of the group to the critical density at redshift  $z$ . The former is given by

$$\rho_{\text{crit}}(z) = \frac{\rho_{\text{crit},0} \Omega_0 (1+z)^3}{\Omega(z)}, \quad (5)$$

where  $\rho_{\text{crit},0}$  is the critical density at  $z = 0$ , and  $\Omega(z)$  is the cosmological density parameter. The latter is given by

$$\Delta_c(z) = 18 \pi^2 + 82x - 39x^2, \quad (6)$$

for the flat universe with cosmological constant (Bryan and Norman 1998). In equation (6), the parameter  $x$  is given by  $x = \Omega(z) - 1$ . The virial temperature of a group is given by

$$\frac{k_B T_{\text{vir}}}{\mu m_H} = \frac{1}{2} \frac{G M_{\text{vir}}}{r_{\text{vir}}}, \quad (7)$$

where  $k_B$  is the Boltzmann constant,  $\mu(= 0.6)$  is the mean molecular weight,  $m_H$  is the hydrogen mass, and  $G$  is the gravitational constant. We assume that IGM had not been affected by non-gravitational heating until blast waves were driven. Thus, since the average mass density of a group is given by  $\Delta_c \rho_{\text{crit}}$ , the average density of the IGG is given by  $\rho_{\text{IGG}} = f_{\text{gas}} \Delta_c \rho_{\text{crit}}$ , where  $f_{\text{gas}}$  is the gas or baryon fraction of the universe. We use  $f_{\text{gas}} = 0.25(h/0.5)^{-3/2}$ , where the present value of the Hubble constant is written as  $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ . The value of  $f_{\text{gas}}$  is the observed gas mass fraction of high-temperature clusters (Mohr, Mathiesen and Evrard 1999; Ettori and Fabian 1999; Arnaud and Evrard 1999), for which the effect of non-gravitational heating is expected to be small.

## 2.2. The Evolution of Blast Waves

The Sedov-Taylor solution for pointlike explosions adequately describes the early phase of the evolution of blast waves. It gives a shock radius of

$$r_s = \xi \left( \frac{E_0}{\rho_{\text{IGG}}} \right)^{1/5} t^{2/5}, \quad (8)$$

where  $\xi = 1.15$ ,  $E_0$  is the explosion energy, and  $t$  is the time elapsed since the explosion (Spitzer 1978).

If  $E_0$  is relatively small, the hot gas region surrounded by a blast wave becomes in pressure equilibrium with the ambient gas before the wave escapes from the group. The radius at which the pressure equilibrium attained is approximately written as

$$r_p = \left( \frac{3E_0}{4\pi P_a} \right)^{1/3}, \quad (9)$$

where  $P_a$  is the pressure of the ambient gas. We call this radius ‘the pressure equilibrium radius’. We assume that the pressure of the ambient gas is given by

$$P_a = \frac{\rho_{\text{IGG}} k_B T_{\text{vir}}}{\mu m_H}. \quad (10)$$

On the other hand, if  $E_0$  is large or  $r_p > r_{\text{vir}}$ , the blast wave escapes from the group and the IGG of the group is expelled.

If the density of IGG,  $\rho_{\text{IGG}}$ , is large, radiative cooling may affect the evolution of blast waves. The postshock temperature is given by

$$T_s = \left( \frac{\mu m_H}{k_B} \right) \frac{8}{25} \frac{(\gamma - 1)}{(\gamma + 1)^2} \xi^2 \left( \frac{E_0}{\rho_{\text{IGG}}} \right)^{2/5} t^{-6/5}, \quad (11)$$

where  $\gamma = 5/3$  is the adiabatic index (Spitzer 1978). The postshock cooling time is given by

$$t_c = \frac{3}{2} \frac{P_s}{n_e n_i \Lambda(T_s)}, \quad (12)$$

where  $P_s$ ,  $n_e$ , and  $n_i$ , respectively, are the pressure, electron density, and ion density of the postshock gas, and  $\Lambda$  is the cooling function. We adopt the cooling function of 1/100 solar metal abundance derived by Sutherland and Dopita (1993). The cooling becomes important when  $t_c < t_{\text{exp}}$ , where  $t_{\text{exp}} = r_s/(dr_s/dt)$  is the expansion time scale. We define the cooling radius  $r_c$  as the one at which the condition  $t_c = t_{\text{exp}}$  is satisfied. If  $r_c < r_p$ , we expect that most of the energy released by an explosion is radiated and is not transferred into IGG.

### 3. Results

We adopt a CDM model with  $\Omega_0 = 0.3$ ,  $\Lambda = 0.7$ ,  $h = 0.7$ , and  $\sigma_8 = 1.0$ . Figures 1a-c show the evolutions of  $r_p$ ,  $r_s$ , and  $r_{\text{vir}}$  of a galaxy group with *present* mass of  $M_0 = 10^{14} M_\odot$ . The input energies are  $E_0 = 10^{61}$ ,  $10^{59}$ , and  $10^{56}$  erg, respectively. We call the model of  $E_0 = 10^{61}$  erg a ‘quasar model’, because the typical energy of a quasar activity is  $\sim 10^{61}$  erg (e.g. Yamada et al. 1999). Moreover, we refer to the models of  $E_0 = 10^{59}$  and  $10^{56}$  erg as a ‘strong starburst model’ and a ‘weak starburst model’, respectively. Note that the energies correspond to the binding energies of galaxies with the mass of  $1.4 \times 10^{11} M_\odot$  and  $1.2 \times 10^9 M_\odot$ , respectively (Saito 1979).

In the quasar model, the radii have a relation of  $r_p < r_{\text{vir}} < r_c$  for  $z \lesssim 1$  (Figure 1a). Thus, the blast wave is confined in the group and the explosion energy is effectively transformed into the IGG. Thus, the IGG is internally heated. On the other hand, for  $z \gtrsim 1$ , the radii have a relation of  $r_{\text{vir}} < r_c < r_p$ , which means that the blast wave escapes from the group, and the IGG is expelled.

The fate of the blast wave in the strong starburst model is qualitatively the same as that in the quasar model; the wave is confined for  $z \lesssim 3$  but gets out of the group for  $z \gtrsim 3$  (Figure 1b). On the other hand, in the weak starburst model, radiative cooling becomes important for  $z \gtrsim 3$  because  $r_c < r_p$  (Figure 1c). Thus, the heating is inefficient for  $z \gtrsim 3$ , although it is efficient for  $z \lesssim 3$  ( $r_c > r_p$ ).

### 4. Discussion

We have investigated the evolution of blast waves in galaxy groups growing on a hierarchical clustering scenario. We found that the blast waves driven by quasars are confined in groups and heat the intragroup gas (IGG) internally at  $z \lesssim 1$ . However, at  $z \gtrsim 1$ , they expel the IGG; the expelled gas may fall back into the groups later as externally heated gas. For the blast waves driven by strong starbursts, the shift of the fate of blast waves occurs at  $z \sim 3$ . On the other hand, the blast waves driven by weak starbursts do not expel IGG, and the heating efficiency decreases at  $z \gtrsim 3$  because of radiative cooling. The results can be used to determine the heating sources of IGG and the heat input epoch by comparing them with the predictions of Tozzi et al. (2000).

Note that several studies have suggested that the energy input by supernovae (including star-

burst galaxies) falls short of the observed energy injection. Using a simple theoretical model, Valageas and Silk (1999) indicated that the energy provided by supernovae cannot raise the entropy of IGG up to the level required by current observations. Moreover, Kravtsov and Yepes (2000) estimated the energy provided by supernovae from the observed metal abundance of X-ray gas and found that the heating only by supernovae requires unrealistically high efficiency. Thus, quasars or AGNs may be the main contributor of the heating of IGG (Wu, Fabian & Nulsen 2000). If this is the case, the energy input epoch is expected to be  $z \sim 2$  at which the number density of quasars reaches the maximum (Hartwick & Schade 1990; Warren, Hewett & Osmer 1994; Schmidt, Schneider & Gunn 1995; Kennefick, Djorgovski & de Carvalho 1995). Our quasar model shows that IGG is expelled from groups by blast waves at  $z \sim 2$  (Figure 1a). Thus, if quasars have mainly heated IGG, we may detect the isentropic, low surface brightness emissions extending to radii larger than the virial ones in groups according to Tozzi et al. (2000).

The IGG expelled by quasars may mix with a large amount of the intergalactic medium (IGM) surrounding the groups. Thus, if metal is ejected from galaxies into the IGG at  $z \gtrsim 2$ , it may be diluted further with the surrounding IGM. X-ray observations show that the metal abundance of IGG is small in comparison with that of X-ray gas in clusters (Renzini 1997; Fukazawa 1997). The observed IGG with low metal abundance may be the IGM later accreted by the groups.

Finally, we make comments on clusters. We have confirmed that the blast waves driven by quasars are confined in clusters with present mass of  $M_0 \gtrsim 10^{15} M_\odot$  for  $z \lesssim 2$  (Figure 2). This may explain the relatively high metal abundance of X-ray gas in rich clusters (Renzini 1997; Fukazawa 1997). Moreover, if quasars are the main heating sources of the X-ray gas in clusters, shock fronts may be detected at the virial boundary of clusters contrary to groups. This is because quasars internally heat the X-ray gas at least for  $z \lesssim 2$  and thus the temperature of infalling IGM may be small (see Tozzi et al. 2000).

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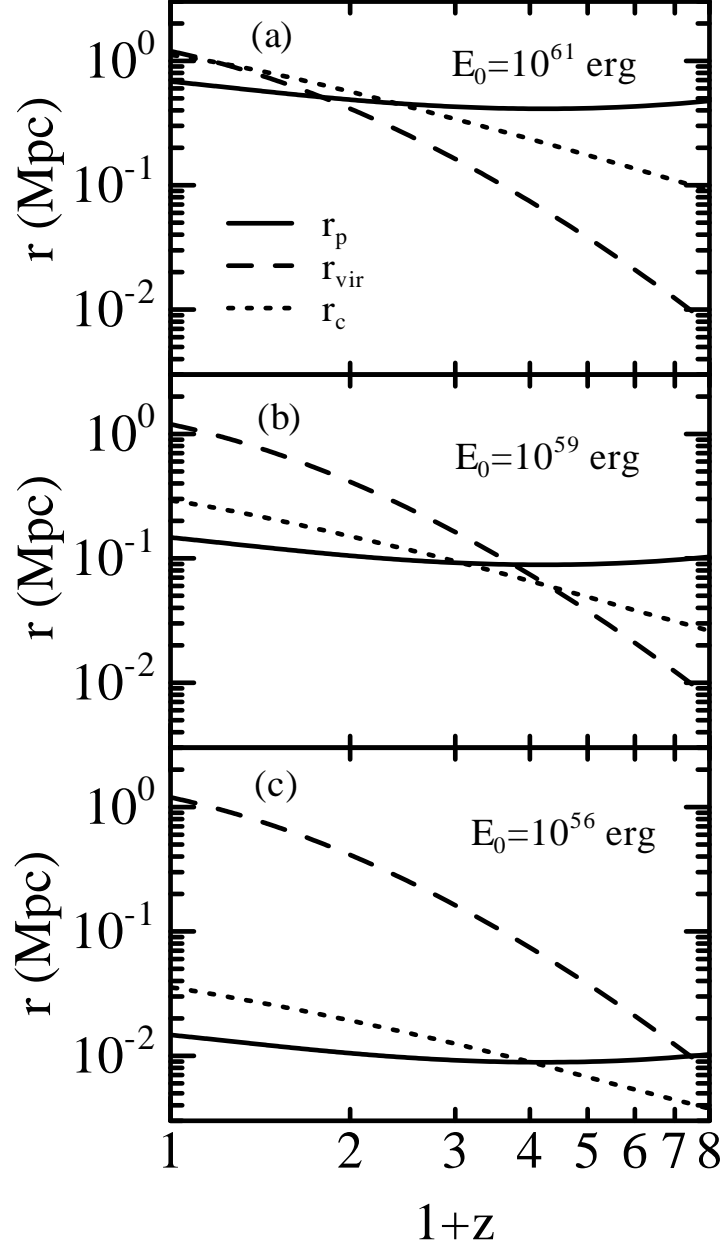


Fig. 1.— The evolutions of the pressure equilibrium radius (solid lines), virial radius (dashed lines), and cooling radius (dotted lines) for a group with  $M_0 = 10^{14} M_\odot$ . (a)  $E_0 = 10^{61}$ , (b)  $E_0 = 10^{59}$ , and (c)  $E_0 = 10^{56}$  erg.



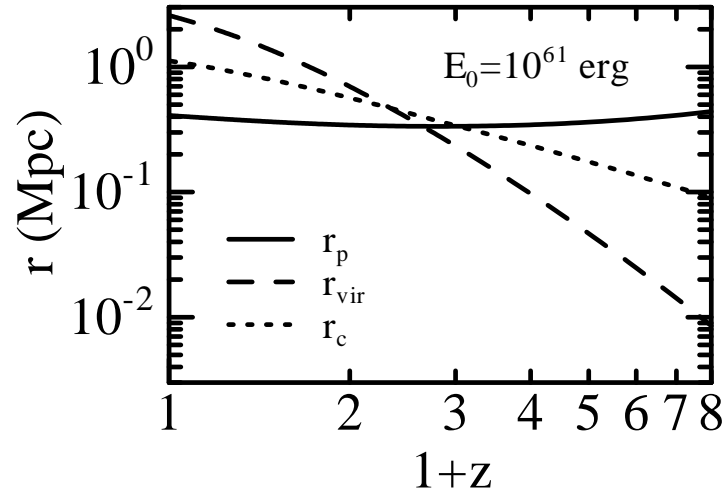


Fig. 2.— The evolutions of the pressure equilibrium radius (a solid line), virial radius (a dashed line), and cooling radius (a dotted line) for a cluster with  $M_0 = 10^{15} M_\odot$ . The explosion energy is  $E_0 = 10^{61} \text{ erg}$ .